The US National Compact Stellarator Program

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The US Compact Stellarator Program Explores Quasi-Symmetry and Stability

Goals: Advance 3D toroidal confinement understanding

- Reduced neoclassical and anomalous transport
- MHD stability; disruption immunity without instability feedback
- Natural divertor for particle & power handling

– Provide improved confinement concept

- Quiescent steady state, without current or rotation drive
- Factor 2-4 lower aspect ratio than conventional stellarators

Integrated Program Elements

NCSX: integrated high-β, low ν^* quasi-axisymmetry

HSX: quasi-helical symmetry

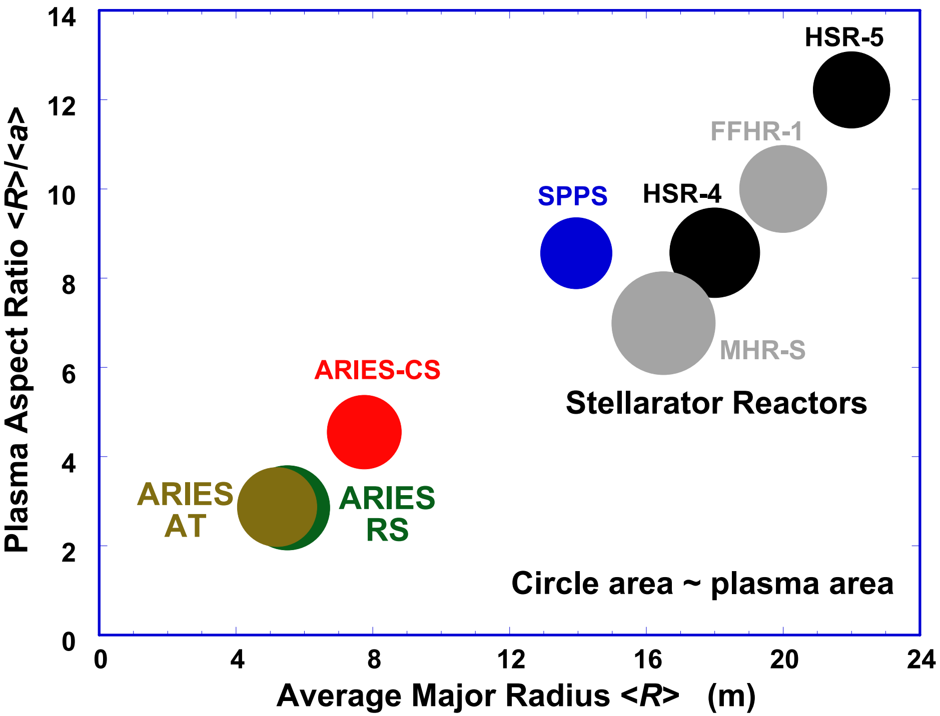
CTH: disruption avoidance

QPS: quasi-poloidal symmetry

Theory and modeling

ARIES reactor studies

International collaborations



The Compact Stellarator Program Addresses Critical Fusion Science Questions

T1.How does magnetic structure impact confinement? What is the effect of 3D shaping on confinement? Is quasi-symmetry effective? How does it differ from axisymmetry?

T2.What limits maximum pressure? Can 3D shaping increase the β limit? What are the β limiting mechanisms with 3D fields and how can they be controlled?

T3.External control and self organization How does 3D shaping affect self-organization of profiles? How high a bootstrap fraction is controllable? Under what conditions are disruptions eliminated?

T4.Turbulent transport How is turbulent transport and transport barriers affected by 3D shaping? How does electron transport depend on local shear and curvature?

T5. Electromagnetic fields and mass flow generation How does 3D flow damping affect zonal flows and turbulence stabilization?

T6.Magnetic field rearrange and dissipate How do shear, pressure, seed perturbations, and ion kinetics affect NTM onset and saturation, in detail?

The Compact Stellarator Program Addresses Critical Fusion Science Questions

T9.How to interface to room temperature surroundings? How is the SOL and PFC interface affected by stochasticity and 3D shaping? Can the interface and exhaust be improved using 3D effects?

T11.Electromagnetic waves interacting with plasma How do RF waves interact with plasma in 3D?

T12.High-energy particles interacting with plasma How does 3D shaping affect energetic-ion instabilities? Can they be stabilized? Can 3D orbit losses of energetic ions be controlled?

T15.How to heat, fuel, confine steady-state or pulsed plasmas? How can we control and fuel a 3D plasma? How much control is required? How can we diagnose the plasma state in 3D?

Compact Stellarator Research Supports, Supplements and Benefits from ITER

Supports ITER

- Help understand effects of 3D magnetic perturbations on plasma equilibrium, stability and boundary, enable extrapolation to ITER to improve performance

Supplements ITER

- Compact stellarators investigate complementary approaches to solving fusion's challenges: steady state, disruption free, high-β, divertor design
- 3D shaping instead of feedback stabilization

Benefits from ITER

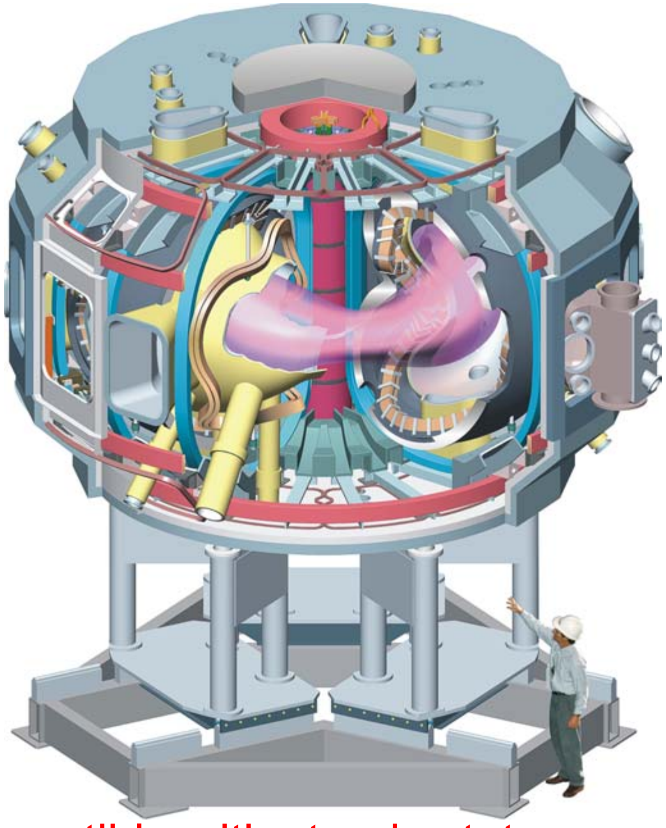
- ITER will explore burning plasmas at the reactor scale
- Understanding from ITER should be directly applicable to quasi-symmetric configurations

NCSX: the PoP Experiment in the Compact Stellarator Program

Mission: Acquire the physics data needed to assess the attractiveness of compact stellarators; advance understanding of 3D fusion science.

Understand…

- Pressure limits and limiting mechanisms
- Stabilization of disruptions
- Reduction of neoclassical transport
  and turbulent transport
- Stabilization of equilibrium islands and NTMs
- 3D power and particle exhaust methods
- Improved energetic-ion stability and confinement



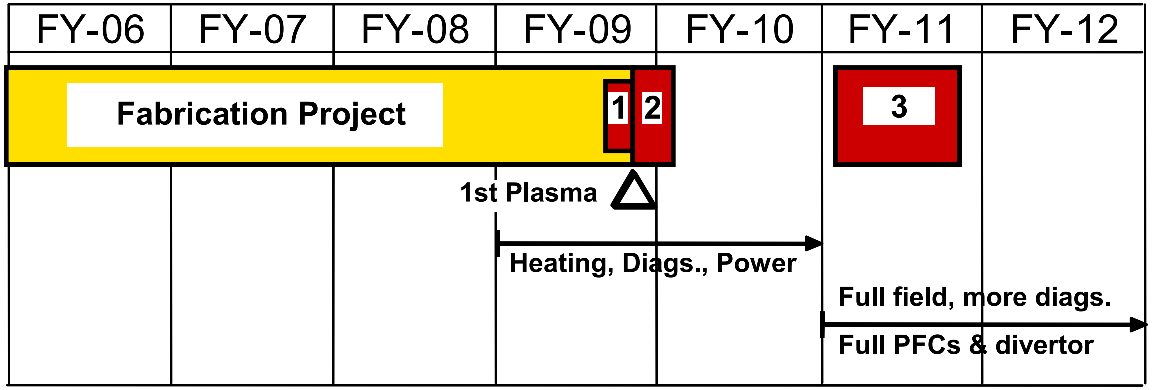
Demonstrate…

- High β, disruption-free operation, good confinement, compatible with steady state

T1, T2, T3, T4, T5, T6, T9, T11, T12, T15

See H. Neilson's talk for discussion of status and budgets

NCSX Research Starts in FY09



Research Campaigns:

1. Stellarator Acceptance Testing & First Plasma (Fabrication Proj.)

2. Magnetic configuration studies
   – Field mapping studies

3. Initial Heating Experiments
   - Effect of quasi-symmetry on confinement, rotation
   - Initial comparisons between measured and calculated linear MHD stability
   - Test of whether linear MHD activity is limiting (e.g. disruptions)
   - Effect of 3D equilibrium on SOL characteristics and contact footprint

NCSX National Collaboration is Forming

Process will be similar to NSTX's

- Annual Research Forums to inform plans and identify collaborator interests.
- Project identifies collaboration needs in a "program letter" to DOE.
- Proposers & project coordinate to ensure common understanding of requirements.
- Proposals go to DOE. DOE decides and provides funding.
- First NCSX proposal call is expected in FY08 for funding in FY09–12.

First Research Forum: 7 December 2006

- 12 presentations by prospective collaborators, strong interest
- Strong interest for International collaboration
  - Germany: 70 GHz ECH
  - Japan: HIBP ?
- Follow-on National theory conference call on NCSX theory needs & collaboration opportunities.

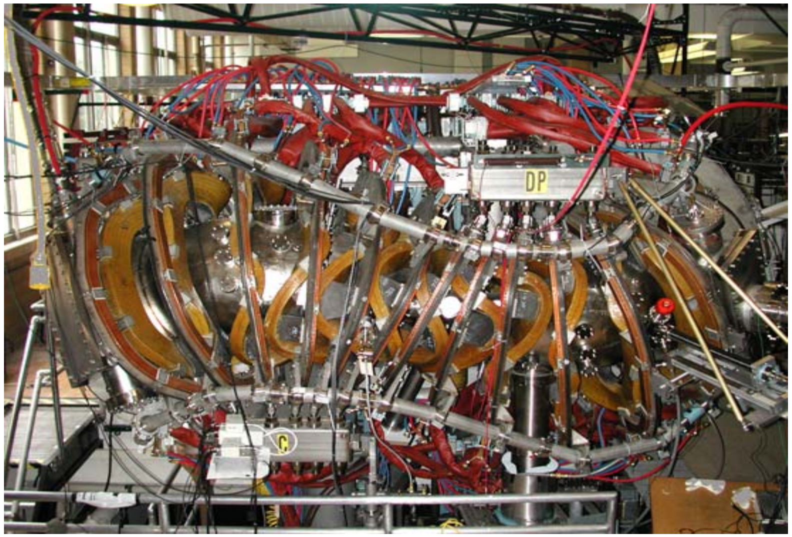
PPPL PRINCETON PLASMA PHYSICS LABORATORY ornl

The Helically Symmetric Experiment (HSX)

University of Wisconsin-Madison

Mission: To demonstrate the potential benefits of quasisymmetry

Plays a unique role in international stellarator program



R = 1.2m $\langle a_p \rangle$ 0.15m B = 1.0T

HSX research contributes to NCSX

- Variation of flows, currents and turbulence with magnetic structure
- 3-D neutral transport modeling/edge structure
- Investigation of ICRH/EBW heating techniques and modeling

Program Role: First experimental test of quasisymmetry worldwide; explore role of effective ripple in reduction of neoclassical/anomalous transport

- Low ripple (<1% at edge)
- Auxiliary coils allow control of ripple, transform and well depth
- High effective transform (~3) unique from QPS/QAS
- ECH provides low collisionality electrons to test transport
- Well diagnosed plasma for a CE experiment

T1, T4, T5, T11, T12

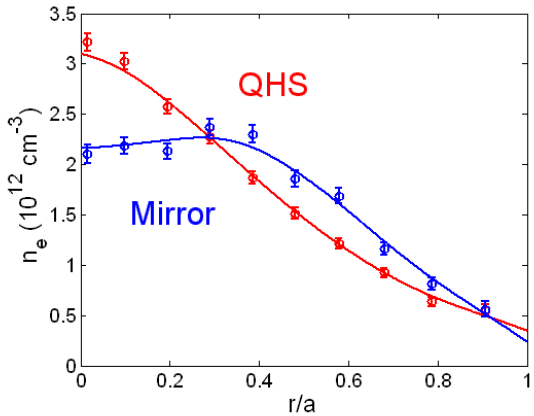
HSX can span between symmetric/non-symmetric configurations

HSX Data supports Quasisymmetry as the Basis of the U.S. Compact Stellarator Program

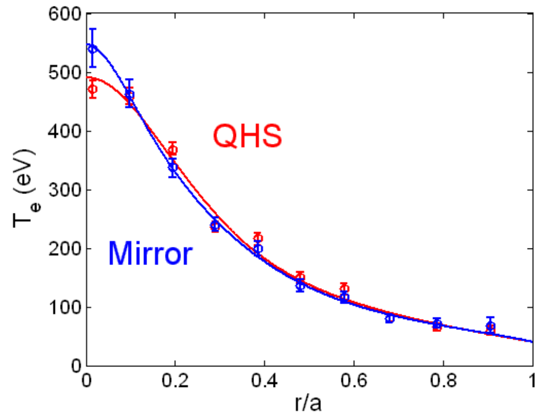
Demonstrated reduced flow damping with quasisymmetry: Gerhardt, PRL 94, 015002 (2005)

Demonstrated reduced neoclassical particle and energy transport:

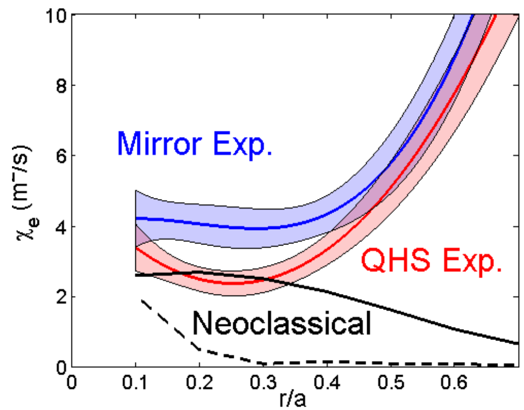
Canik, PRL 98, 085002 (2007)



Reduced thermodiffusion with quasisymmetry



2.5 times the power needed in mirror to match T_e profiles



Calculated reduced central χ_e even in electron root ($T_e >> T_i$)

Program Directions: Now operating at B=1.0T with increased ECH power

What is optimal level of quasisymmetry?

- Measurement of E and comparison to neoclassical theory
- Test whether anomalous transport is reduced with lower effective ripple
- Investigate possibility of increased zonal flows due to lower momentum damping
- Measurement of bootstrap current with varying magnetic field spectrum
- Increase ion temperatures to access ion-root discharges

HSX Research Severely Impacted by Continual Budget Cuts During Time of High Productivity

FY07 ICC cut:

Terminated 1 technician (of 3),
and ½ scientist

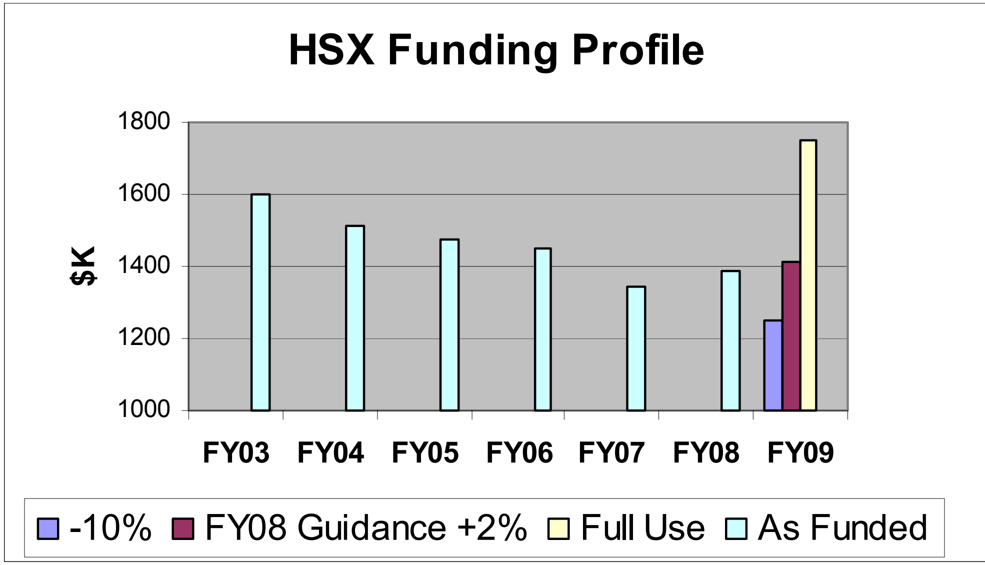
no replacement of postdoc

2 grad student reduction

no undergrads

FY08 guidance: will force

80K salary reduction to provide funds for effective operations



Flat or Decrement Budgets in FY09 Limit HSX Research Opportunities

FY09 +2% from FY08 ($1415K guidance) :

- Loss of a student to cover escalation
- Pace slows on 2nd ECH system
- New diagnostics: CHERS and reflectometer

FY09 10% decrement ($1248K):

- Loss of 1 additional FTE scientist and one additional graduate student
- Work stops on the 2nd ECH system/No EBW or pulse propagation experiments
- New students only with fellowships/scholarships; no new diagnostics

Full Use Budget Restores High Research Productivity

FY09 Full Use ($1750K):

- Implementation of second 28 GHz gyrotron, increase power to 400 kW;

  steerable launcher

  pulse modulation experiments, profile control, expanded heating power, EBW

- Low power ICRF antenna design/fabrication for loading/feasibility studies

  Ion heating for ion-root plasmas to accentuate differences between QS/non-QS operation

- Implement HIBP with RPI using existing accelerator (at RPI)

- Hire a replacement for postdoc

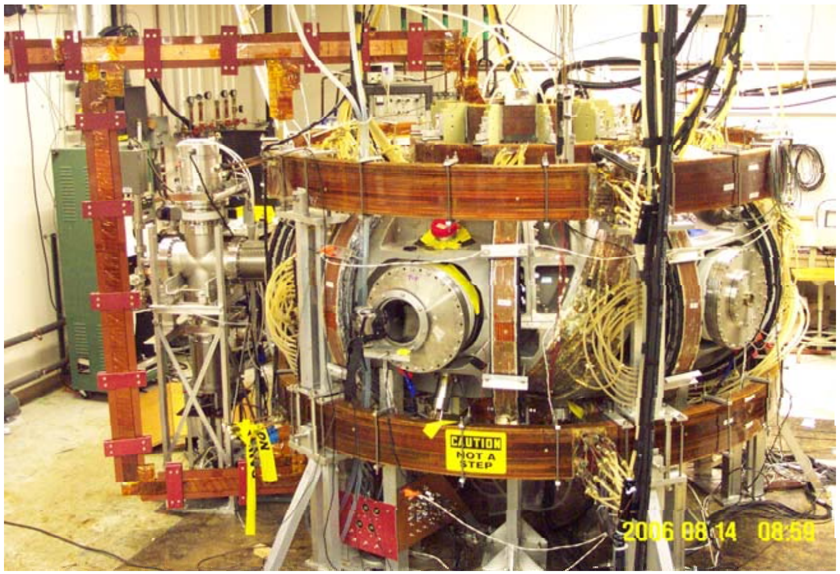
- Measurement and modeling edge/divertor structure and neutral particle transport

  Collaborations with ORNL/PPPL team; input for PFC/divertor designs

The Compact Toroidal Hybrid (CTH)

Auburn University

Mission: pursue equilibrium and stability in current-carrying compact stellarators as element of US Compact Stellarator Program



Program role:

- Fundamental study of passive disruption avoidance and immunity in toroidal 3D plasmas
- Validate new methods of magnetic equilibrium measurement in 3-D plasma.
- Control static islands in low-aspect ratio helical systems for understanding and improvement of equilibrium and stability.

CTH research contributes to NCSX

- Field-mapping to update vacuum field model.
- Reconstruction of 3-D equilibria
- Scoping of low-β MHD stability

T3

CTH FY09 plans follow from FY08 goals and FY07 progress

FY07 progress

- Driven current substantially modifies vacuum magnetic configuration, thus far without disruptions.
  - Fundamental equilibrium and stability studies underway

FY08 goals

- Exploration of stability with external control of vacuum rotational transform and shear with magnetic and SXR diode arrays.
- Use of new V3FIT code for 3D equilibrium reconstruction in stellarators.
- Understand effect of controlled static islands, stochastic fields on edge parameters and flows (NEW)

FY09 plans

- Additional ECRH power for hotter target plasmas (NEW)
  - Potential test of EBW heating for NCSX
- Continue investigation of stability and equilibrium (CTH fundamental mission) of current-carrying stellarator plasmas
  - measure current profile with internal B-field diagnostic (NEW)
- Collaborate on NCSX (field-mapping) (NEW)

CTH FY09 plan remains severely constricted

Current staff: 1 academic PI, 1 research scientist co-PI, 1 technician
2 graduate students, 2 undergraduates

Base Budgets

FY2006	$445K		
FY2007	$407		
FY2008	$418 (projected 2.7% COLA)		
FY2009	10% decrement	target	full-use
	$376K	$426K	$500K
			(original budget)

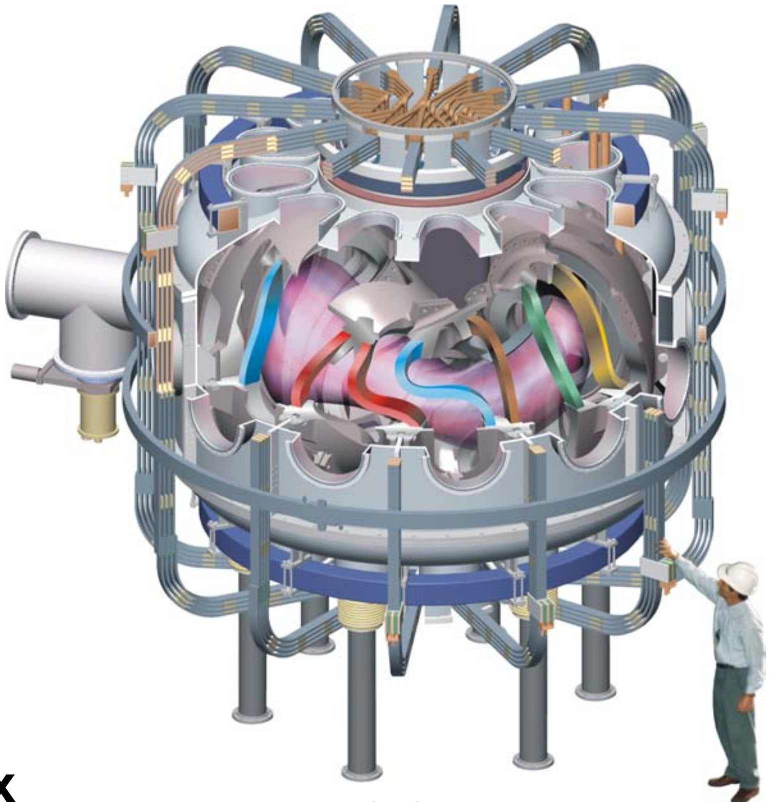
FY09 full use plan
- Achievement of 3D reconstruction capability with ext. magnetic loops, SXR arrays, internal magnetic measurement
- Adequately-diagnosed current-driven instability studies
- Additional ECRH heating
- 4 graduate students

FY09 target
- Maintain present reduced level of effort. Maintain facility.
- No additional diagnostic system (for internal B measurement) or plasma heating.
- 2-3 graduate students.

FY09 decrement
- Operational funds restricted to support key maintenance issues.
- Critical reduction of manpower: 2 graduate students (max.), academic PI participation reduced or eliminated

QPS is needed to test low-R/a Quasi-Poloidal Symmetry

- **Completes assessment of compact stellarator strategies**
- **Linked-mirror-like geometry permits very large flows & flow shearing**
  - Self-generated E x B flows reduce neoclassical & anomalous transport
  - >10x larger poloidal flow shear than other toroidal devices
  - reduced growth rates for trapped particle, ITG modes
- **Can vary key physics features by >10x**
  - quasi-poloidal symmetry, poloidal flow damping, neoclassical transport
  - stellarator ⇔ tokamak shear
  - trapped-particle fraction

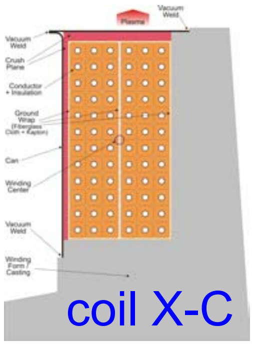


- **$\langle R \rangle$ = 0.95 m**
- **$\langle a \rangle$ = 0.3-0.4 m**
- **$\langle R \rangle / \langle a \rangle$ > 2.3**
- **B = 1 T, P = 3-5 MW**

ornl THE UNIVERSITY of TENNESSEE PPPL PRINCETON PLASMA PHYSICS LABORATORY UT-BATTELLE

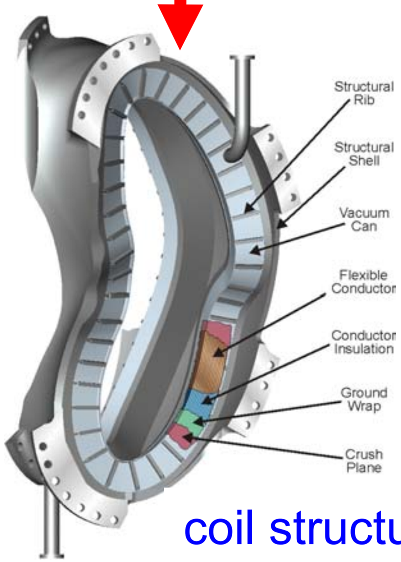
QPS R&D is demonstrating manufacturing solutions to reduce cost and risk prior to project start in 2008-9.

- **Incorporates knowledge gained in NCSX project**
- **2007: finish machining 1st modular coil winding form & coil R&D**



coil X-C

  – Flexible, internally cooled cable conductor
  – Novel hi-temp. cyanate ester for potting in vacuum can
  ⇒ July-07: full-scale vacuum-tight coil canning concept
  ⇒ Sept-07: wind full X-C, partial size R & D coil



coil structure cutaway

3-D machining of 4-ton form @ Keystone Eng.

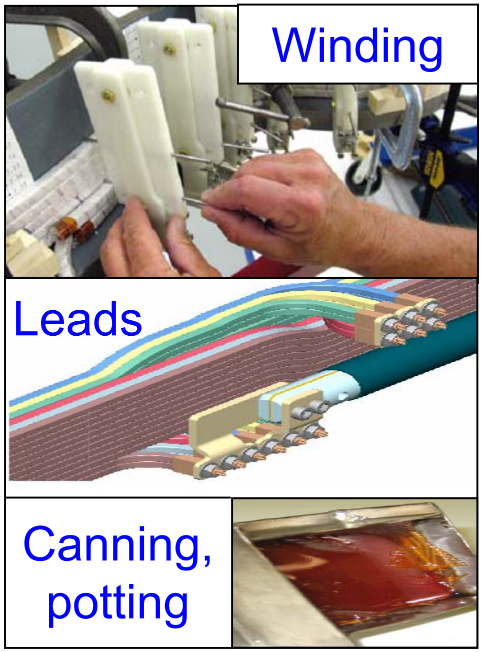
On winding fixture at U Tenn. Magnet Dev. Lab.

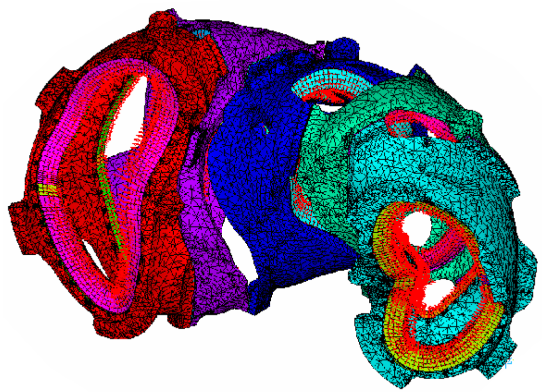
FY 2008: QPS Progressing Toward Project Start

- **FY 2008: complete preparations for coil production**

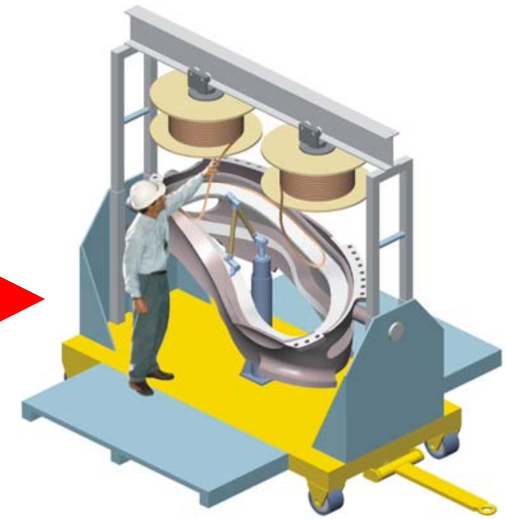
⇒March-08: Complete vacuum canning & potting full-X-C, partial-size R&D coil

⇒Sept-08: Complete QPS preliminary design





3-D stress analysis,
heat transfer



Ready for production
at U. Tenn

- **FY 2008 Presidential budget: ORNL $842k; PPPL $274k**
  - $136k *reduction* from FY 06; $367k *reduction* from FY 05
  - Restoration of even the smaller cut would advance coil winding and potting by 2-3 months

FY 2008/09: Increments needed to start construction

- **FY 2009: $842k at ORNL + UTK, $274k at PPPL**
  - March-09: complete winding prototype coil
  - Sept-09: complete canning, potting & testing prototype coil
- **10% decrement (additional $112k reduction)**
  - Drop support for 2 U Tenn. graduate students, 1 faculty
  - Delay completing prototype coil and final design to 2010
- **Requested increments $\Rightarrow$ QPS project start in 2008/09**
  - $3.15M/$4.14M ORNL+UT-K, $2.36M/$2.44M PPPL
  - April-08: Prelim. Design & External Reviews
  - Aug-08: Final Design Rev. for winding forms & vac. vessel
  - Sept-09: begin winding first production coil

US Stellarator Theory is Crucial

- Necessary to support, interpret and extrapolate experiments

- US leads the world program in 3D equilibrium modeling and stellarator configurations design

- Significant efforts ongoing or planned on
  - Equilibrium reconstruction
  - Non-linear MHD stability
  - Alfvenic and fast-ion instabilities
  - Turbulence modeling

- Also engaged in understanding tokamaks with 3D magnetic perturbations
  - e.g. with resonant magnetic perturbations for ELM control.

US Compact Stellarator Program is Providing Solutions to Fusion Challenges

- Quasi-symmetry resolves neoclassical transport issues of 3D, experimentally gives improved confinement
- Lower aspect ratio gives smaller reactor designs
- Provides path to steady-state, high-β at high density, without disruptions or need for current drive
- Supports, supplements, and benefits from ITER and tokamak program
- Compact, quasi-symmetric stellarators are an area of clear US leadership
- Supporting experiments need incremental funding to achieve goals, take advantage of unique capabilities.